Predicting Geomorphic Change during Large Floods in Semiarid Landscapes

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INTRODUCTION

Predicting where erosion and geomorphic change is expected due to flooding is valuable for the management of stream corridors as well as for specific project planning and design development. Geomorphic change and subsequent flood hazards include localized streambank erosion, hillslope and terrace failure, reach-scale channel widening, sediment deposition and associated loss of channel and floodplain capacity, rapid downstream meander migration, and channel avulsions and braiding. Human encroachments into stream corridors for building such features as roadway and railroad alignments, commercial developments, private residences, and other structures are prime causes for reduced infrastructure resilience and loss of investment.

Where allowed by the valley form, management plans and project designs should provide for sufficient floodplain extent and connectivity to diminish the effects of erosive forces on streambanks, floodplain and terrace surfaces, infrastructure and property, and riparian and aquatic habitats. Yochum et al. (2017) identify unit stream power thresholds for several categories of geomorphic change resulting from the 2013 Colorado Front Range flood; these results are relevant to other semi-arid streams, and are summarized here for use by practitioners. Note that these thresholds are only potentially appropriate for erosion-dominated situations in channels with slopes < 3%.

BACKGROUND

In September of 2013 large portions of the Colorado Front Range foothills received heavy rainfall, with up to 460 mm (18 inches) falling in 10 days and the majority falling during 36 hours on September 11 and 12. The overall depths are similar to the average annual rainfall of these areas. In response, a large number of landslides and debris flows occurred (>1100, Coe et al. 2014), and streams flooded across a wide range of stream types, from steep foothills creeks to high plains rivers. Return periods of peak discharges within the study area ranged from moderate (25- to 50-year) to extreme (≥100-year). Streams throughout the flooded areas were destabilized in many locations (Figures 1 and 2), leading to infrastructure, homes, and businesses being damaged or destroyed, an estimated $2.9B in damages, and 9 human deaths (Aguilar 2014).

Figure 1: Eradicated US-34 roadway embankment along the Big Thompson River on the Roosevelt National Forest (10/21/2013). Peak discharge = ~430 m^3/s (15,000 cfs); ω = 2700 W/m^2. Flow direction is away from viewer. Graphic created in ArcGlobe with imagery from the Colorado Department of Transportation and LiDAR data from FEMA and USGS.

Using the wide-ranging impacts of this flood as examples of geomorphic change, Yochum et al. (2017) utilized several approaches to explain the variable responses across the flood-impacted areas. Geomorphic change prediction is complicated by variability in driving mechanisms (peak discharge, flow duration, channel and floodplain slope, stream power, etc.) and resisting mechanisms (flow resistance, bank composition, vegetation type and extent, rip rap, etc.). This summary report focuses on unit stream power thresholds and provides only a brief overview. For additional details, refer to the peer-reviewed publication.

Figure 2: Residences directly impacted by erosion and geomorphic change during the 2013 Colorado Front Range flood, on the Big Thompson River in Drake (photo credit: NRCS Emergency Watershed Protection program).

Unit stream power has long been used for quantifying the power of moving water that drives sediment transport and geomorphic change. It is computed as

$$\omega = \frac{\gamma Q S_f}{w}$$

where ω is unit stream power (W/m^2), γ is the specific weight of water (N/m^3), S_f is the friction slope (m/m, frequently assumed to be equal to the water surface or channel slope), and w is the flow width (m). Combining peak flow unit stream power with a variety of observed geomorphic changes, thresholds for observed geomorphic change were developed.

A qualitative classification scheme was developed to describe geomorphic change of each stream reach. The ordinal scheme was developed using remotely-sensed and field-based observations of the variety of geomorphic adjustments that were caused by this flood. The following class definitions were used:

(1) No detected geomorphic change.

(2) Infrequent eroded streambanks (<25% of overall streambank length).

(3) Numerous eroded streambanks (>25% of overall streambank length).

(4) Substantially widened channel over the majority of the reach length.

(5) Major geomorphic change, with avulsions, braiding, or roadway embankments and high terraces eliminated or substantially eroded by erosional and/or depositional processes.

An additional category (6) was recognized for those reaches where narrow valley form (e.g. canyon) limited geomorphic adjustment potential and no substantial pre-flood floodplains were detected.

KEY RESULTS

A total of 531 reaches were assessed on 226 km of streams impacted to various extent by the flooding. A variety of stream channel scales and types were included in the analysis, with watershed areas of 4.3 to 2900 km^2 and stream channel slopes from 0.2 to 10.5%.

To accommodate a precautionary approach to management and design, the 10th and 90th percentiles of ω associated with channel changes (Figure 3) were used to indicate the relative likelihood of substantial geomorphic change. Based on this data set, stream channels with <3% slope have a

- credible potential for channel widening where ω is > 230 W/m^2;
- credible potential for avulsions or braiding (caused by erosion-dominated processes) and loss of adjacent roadway embankments with ω > 480 W/m^2; and
- with ω > 700 W/m^2, infrequent to numerous eroded banks are very likely, and the risk of substantial channel widening or major geomorphic change shifts from credible to likely.

Credible potential refers to 10% of the class 4 reaches having ω < 230 W/m^2 and 10% of the class 5 reaches having ω < 480 W/m^2 (excluding depositional-related instability; 2nd and 3rd columns of Figure 3B), and very likely refers to 90% of the combined classes 2 and 3 having ω < 700 W/m2 (1st column of Figure 3B).

These thresholds can be utilized for assessing the geomorphic hazard potential via hydraulic modeling. However, two important exceptions to these thresholds are present:

- Stream channels with slopes >3% resisted geomorphic change at higher ω, likely because of greater erosion resistance and enhanced flow resistance induced from bedform flow dynamics forced by large clasts and, where available, large instream wood. Therefore, these thresholds are not applicable in channels with slopes >3%.
- These thresholds are also not applicable below valley transitions where streams shift from confined to unconfined and unit stream power precipitously drops in magnitude, inducing sediment and large wood deposition. Channel instability induced from deposition resulted in major reach-scale geomorphic change at relatively low ω at some locations, on average about 170 W/m^2 and as low as 86 W/m^2. This effect can result in increased geomorphic change for several kilometers downstream of valley confinement transitions.

These results indicate that using ω thresholds for predicting expected future adjustments of stream channels within and along the Colorado Front Range during floods is reasonable in channels with slopes <3%, though it needs to be understood that there is still a potential for large amounts of geomorphic change below these thresholds along streams where stream power substantially and abruptly decreases. While it is unknown if these results are applicable beyond the analysis extent, in the absence of alternatives the thresholds presented in this work can be utilized in other semiarid areas under the oversight of a qualified professional. However, it is not recommended that these thresholds be utilized in humid areas, due to greater magnitude and variability in resisting forces to geomorphic change.

HYPOTHETICAL EXERCISE

Consider a highway realignment project being designed in a semi-arid riparian setting in western North America. The stream has an average slope of 1.8%, is semiconfined by valley form, and has varying floodplains widths between a steep valley wall and an existing 2-lane state highway. The roadway is planned to be expanded from 2 to 4 lanes, plus bicycle lanes, wider shoulders, and periodic pullout locations and parking for scenic overlooks and National Forest trailheads. This highway is an emergency evacuation route for a downstream community. The initial design is to further constrain the riparian zone by filling the valley bottom for the expanded roadway and associated features; however, there is concern regarding resilience.

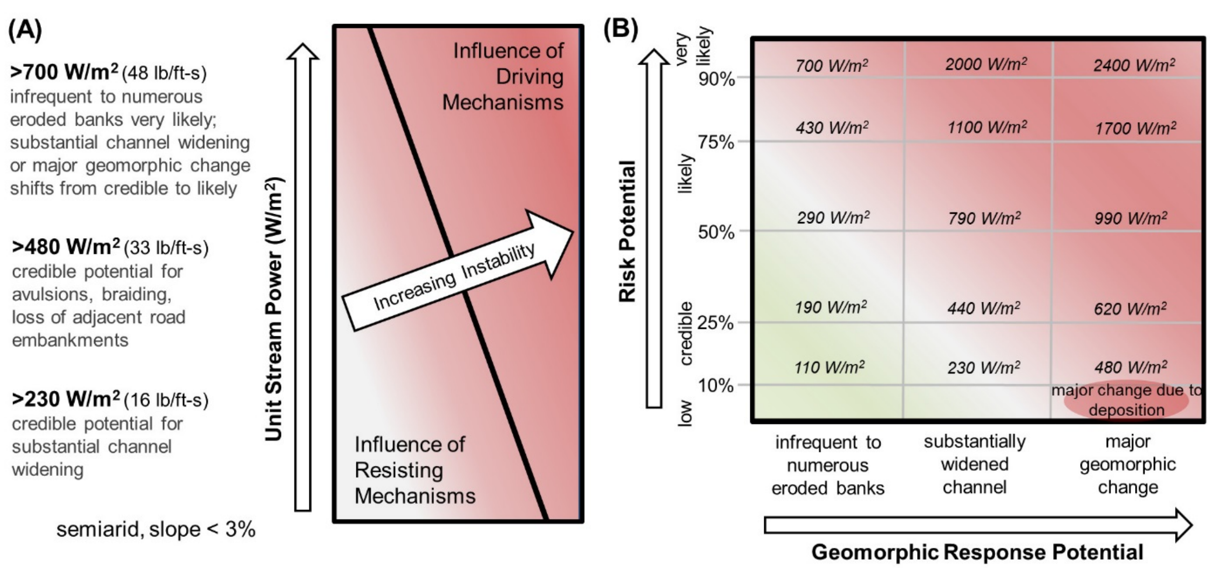

Figure 3: Schematic illustrating conceptual processes and observed thresholds for dominant geomorphic change processes for semiarid streams with slopes <3% during the 2013 Colorado Front Range flood (A) and a risk potential matrix (based on peak flow ω) for three classes of geomorphic adjustments (B). The red oval represents stream reaches with major geomorphic change induced by deposition at relatively low ω. (Figure initially published in Yochum et al. 2017.)

Will this design result in a highway corridor that is substantially more susceptible to geomorphic failure during large floods? With the current design, should an increase in damage potential to the riparian zone be expected from flooding?

The professional engineer overseeing the project searched the available scientific literature and found this work, noting that Figure 3 provides a tool for assessing potential resilience in a quantitative manner. Additional search indicated that no additional relevant research is available for the project area. Based on LiDAR data supplemented with an in-channel feature survey, a DEM was developed for existing conditions and land development software was utilized to create proposed conditions. Using data from a nearby streamgage, a flow-frequency analysis was performed using standard procedures (IACWD 1982). One-dimensional gradually-varied steady state hydraulic models were developed in HEC-RAS for both existing and proposed conditions. At each cross section, ω for the channel and both floodplains were outputted from the models for the 1% chance of exceedance flood (100-year return interval) and compared between existing and proposed conditions (flood elevations, shear stress, velocity, and Froude numbers were also inspected). The modeling was performed in the English unit system, as is typical in the United States. Though for the sake of unit consistency, the results are presented here in the SI system.

The modeling results show longitudinal variability in ω throughout the project reach and between existing and proposed conditions. However, there were no dramatic longitudinal decreases in ω that indicate a potential for depositional-induced geomorphic instability (bottom right corner of Figure 3B); the technical team focused on the potential for erosion-induced instability of the proposed conditions. The modeling indicates that the proposed conditions would, on average, increase ω from 190 to 280 W/m^2, with some proposed locations experiencing ω of 550 W/m^2 and one location where ω would be 800 W/m^2 during the 100-year flood.

Using the thresholds provided in Figure 3A and a precautionary approach, it was noted that the proposed conditions have, on average, a credible potential for channel widening and, in some locations, a credible potential for avulsions and the loss of the road embankment. At one location it is likely that a portion of the roadway embankment on this emergency evacuation route would be endangered during large floods. Using the matrix provided in Figure 3B it is indicated that the reach modeled at 800 W/m^2 is of special concern since, during the 2013 Colorado Front Range Flood, at this unit stream power infrequent to numerous eroded banks were very likely, a substantially widened channel was likely, and there was a credible risk of major geomorphic change. This was the case despite the frequent presence of engineering bank stabilization, such as rip rap. Additionally, the locations where ω reaches 550 W/m^2 highlight points of concern to the roadway stability, while the increase of the average ω to 280 W/m^2 indicate an increased potential for channel widening and, hence, a possible threat to riparian condition. Based on extrapolation from the Colorado data, it was also noted that existing conditions would have a 25% chance of experiencing infrequent to numerous eroded streambanks during a 100-year flood.

Considering these results and the precautionary principle, the lead engineer decided that design modifications were required to reduce the likelihood of roadway embankment failure, with the need for considering additional blasting of valley walls as well as hauling and disposing of material to non-riparian areas outside the project extent. Other alternatives may also be considered but need to consider the riparian resources on the National Forest. Consultation with the Forest Service regarding potential threats to stream channel stability and riparian health was scheduled.

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